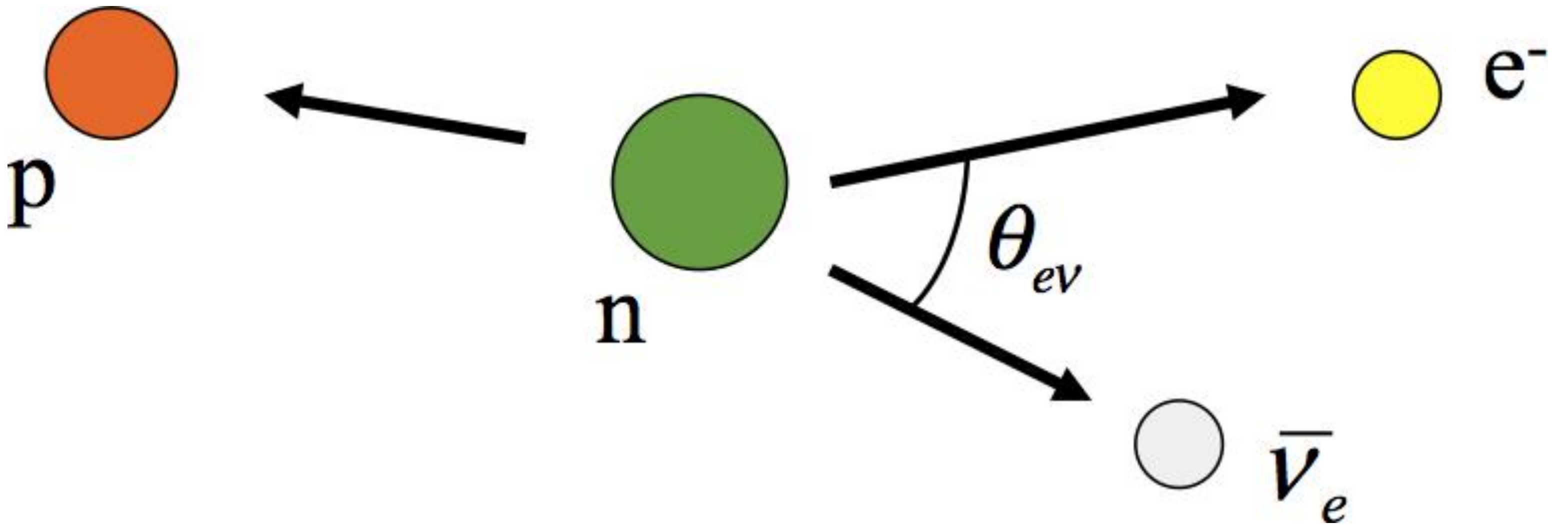
A Precision Measurement of Zero Beam Polarization for the Nab Experiment at the SNS



Chelsea Hendrus
For the Nab Collaboration
April 11, 2022

The Nab Experiment

$$\frac{\partial^5\omega}{\partial E\partial\Omega_e\partial\Omega_\nu} \propto \left[1 + a\frac{\vec{p_e}\cdot\vec{p_\nu}}{E_eE_\nu} + b\frac{m_e}{E_e} + \langle\vec{\sigma_n}\rangle\cdot\left(A\frac{\vec{p_e}}{E_e}+B\frac{\vec{p_\nu}}{E_\nu}+D\frac{\vec{p_e}\times\vec{p_\nu}}{E_eE_\nu}\right)\right]$$

Experimental Goal: $\frac{\Delta a}{a} = 0.1\%$ $\quad a = -0.1044 \pm 0.0008$

$\Delta b = 3 \times 10^{-3}$ $\quad b = 0.017 \pm 0.020$

These parameters contribute to our understanding of Standard Model puzzles

- CKM Unitarity, Quark Mixing V_{ud}
- $\lambda = \frac{G_A}{G_V}$
- Neutron Lifetime

A measurement of b also helps probe Non-Standard Model Physics

The Nab Spectrometer and Detectors

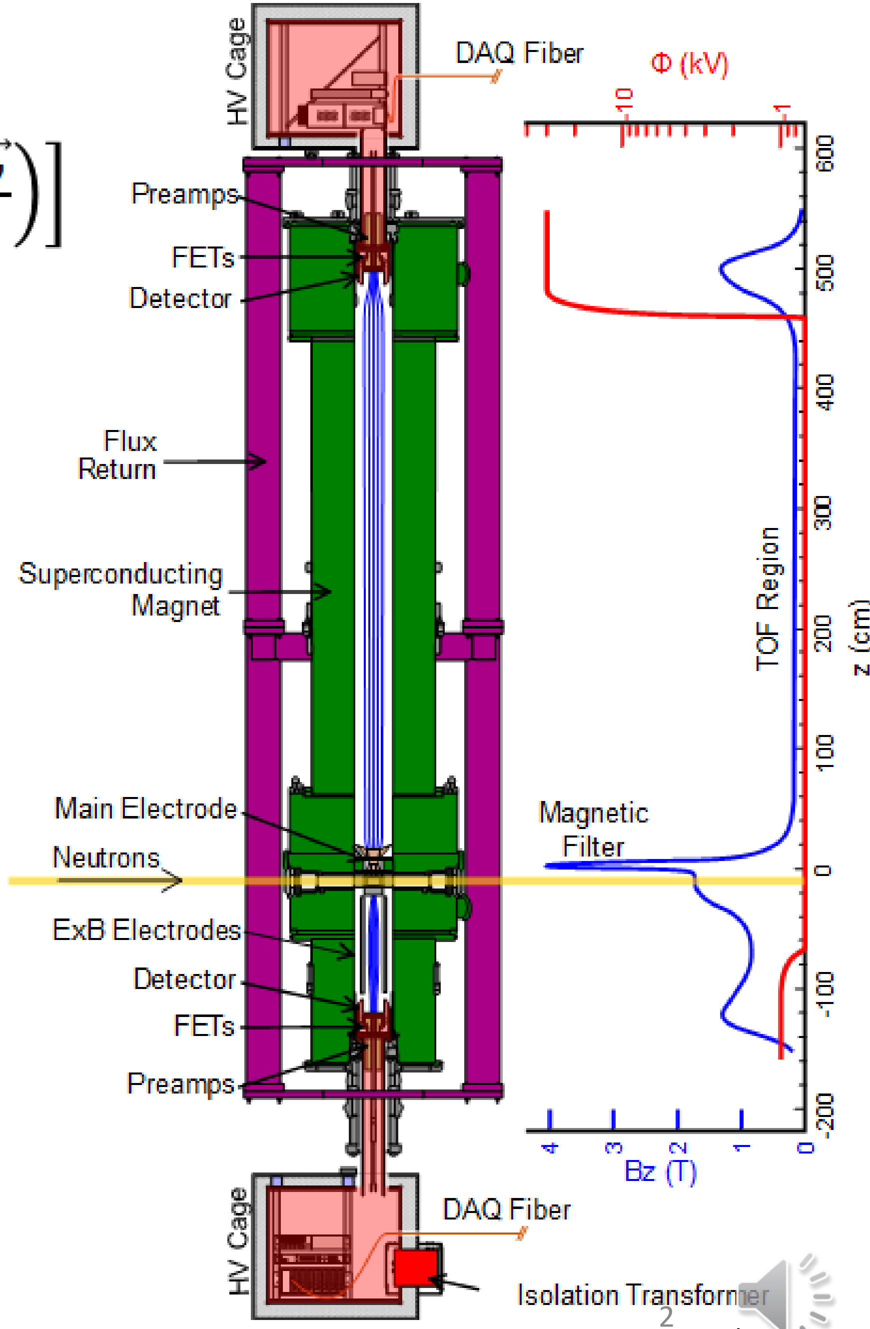


Image: A. Jezghani

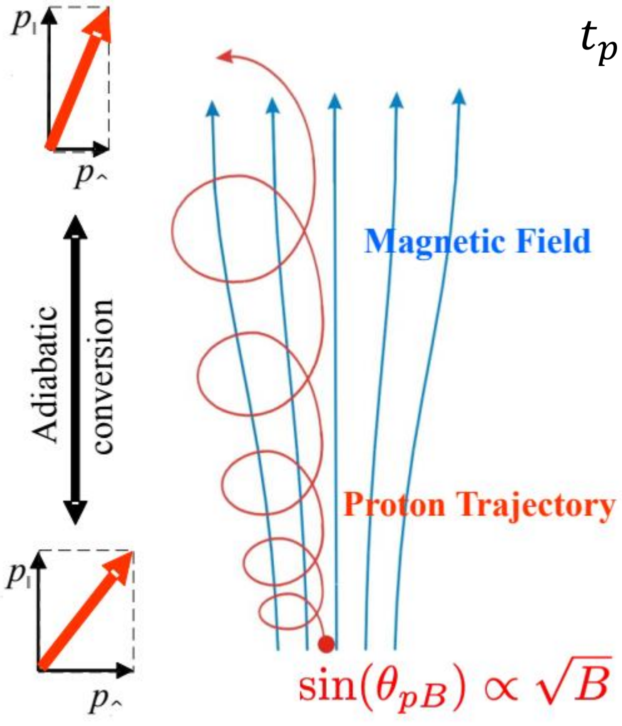
P.A. Zyla et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2020) and 2021 update

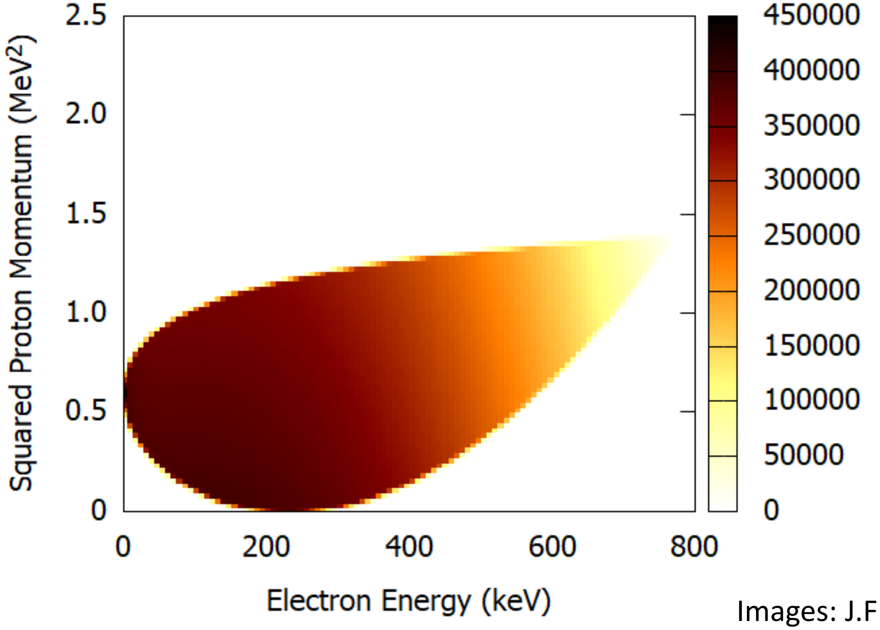
The Nab Experiment

The Measurement:

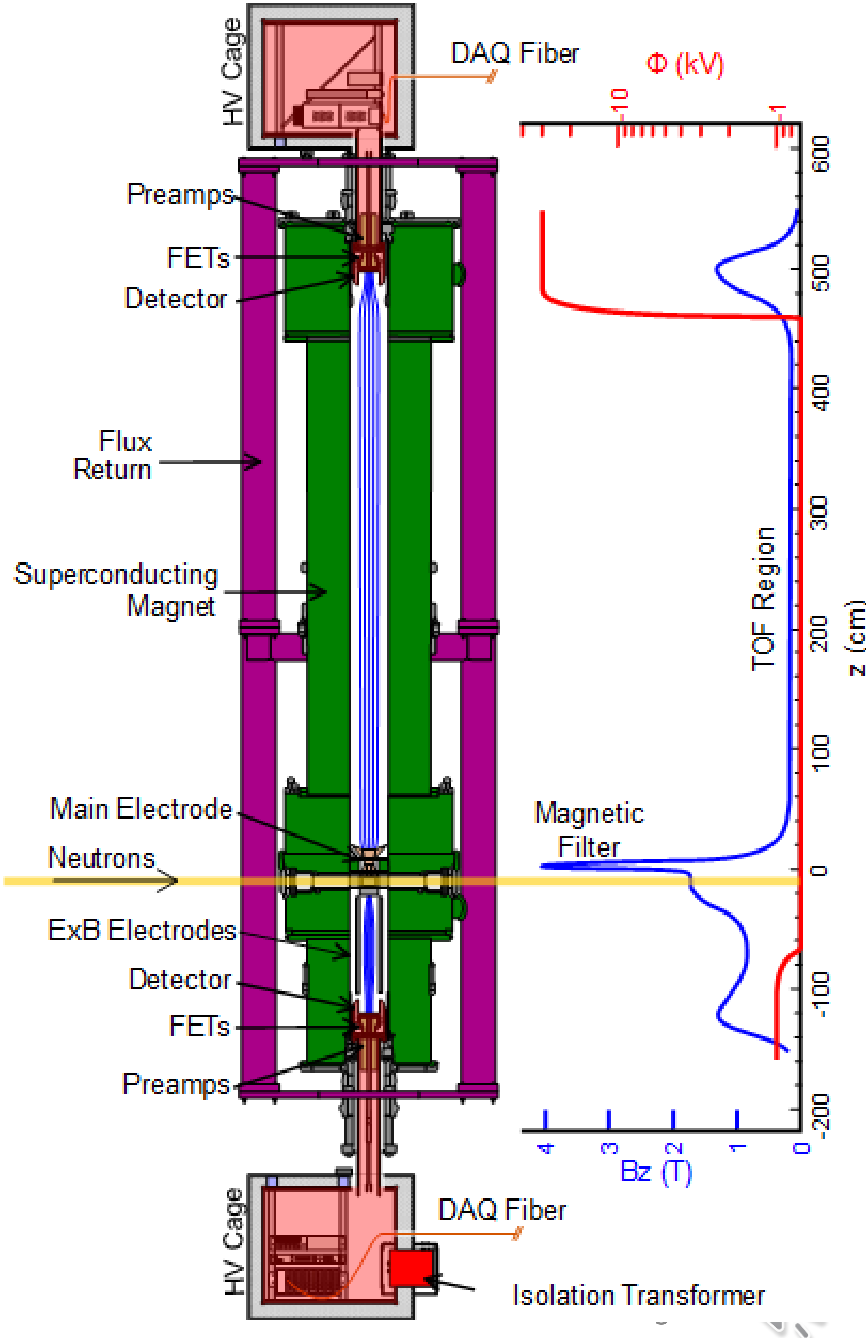
- Measure Electron energy via lower silicon detectors
- Measure proton momentum via Time-of-Flight through Spectrometer field

$$t_p = \frac{m_p}{p_p}\int_{z_0}^{l}\frac{\partial z}{\sqrt{1-\frac{B(z)}{B_0}\sin^2\theta_{p,0}+\frac{q(V(z)-V_0)}{E_{p,0}}}}$$





The Nab Spectrometer and Detectors

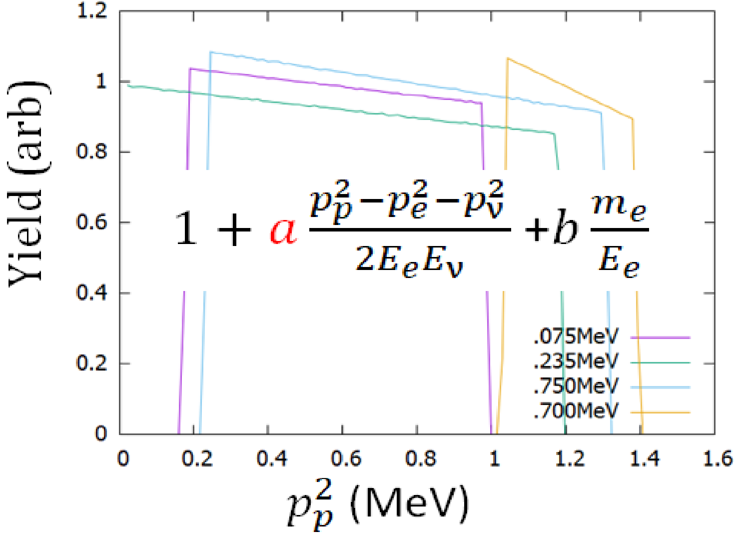


Images: J.Fry, A. Jezghani

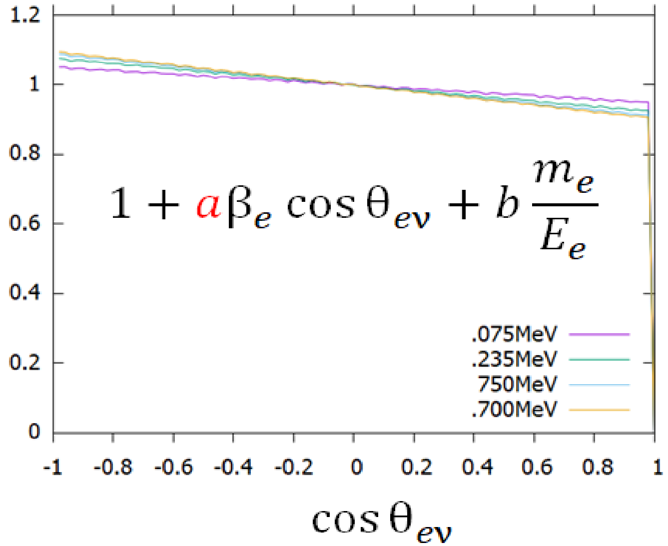
The Nab Experiment

$$\frac{\partial^5\omega}{\partial E\partial\Omega_e\partial\Omega_\nu} \propto \left[1 + a\frac{\vec{p_e}\cdot\vec{p_\nu}}{E_eE_\nu} + b\frac{m_e}{E_e} + \langle\vec{\sigma_n}\rangle\cdot\left(A\frac{\vec{p_e}}{E_e} + B\frac{\vec{p_\nu}}{E_\nu} + D\frac{\vec{p_e}\times\vec{p_\nu}}{E_eE_\nu}\right)\right]$$

Phase spaces of the unpolarized part:



$$1 + a\frac{p_p^2-p_e^2-p_\nu^2}{2E_eE_\nu} + b\frac{m_e}{E_e}$$



$$1 + a\beta_e\cos\theta_{e\nu} + b\frac{m_e}{E_e}$$

Neglect time reversal terms, and average the polarized terms over the events the detector sees we get:

$$\langle\vec{\sigma_n}\rangle\cdot\left(A\frac{\vec{p_e}}{E_e}+B\frac{\vec{p_\nu}}{E_\nu}+D\cancel{\frac{\vec{p_e}\times\vec{p_\nu}}{E_eE_\nu}}\right) \longrightarrow |\langle\sigma_n\rangle|(A\beta_e\langle\cos\theta_e\rangle + \boxed{B\langle\cos\theta_e\rangle\ \cos\theta_{e\nu}})$$

To Meet Our Experimental Goal we must verify that that the beam polarization is:

$$\frac{\Delta a}{a} = \frac{B\langle cos\theta_e\rangle|\langle\sigma_n\rangle|}{\beta_e a} \approx 10^{-4}$$

$$|\langle\sigma_n\rangle| < 2\times10^{-5}$$

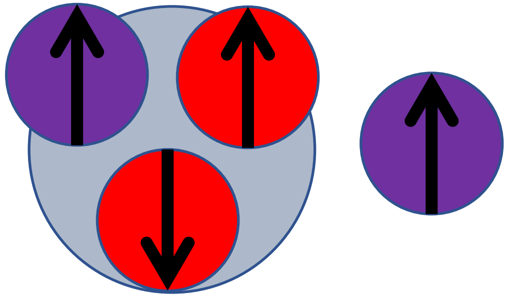
Polarimetry for the Nab Experiment

Neutron Polarizer

The Cross section between ^{3}He and neutrons is spin dependent
They only interact in the singlet state!

Transmission of Neutrons through Unpolarized ^{3}He

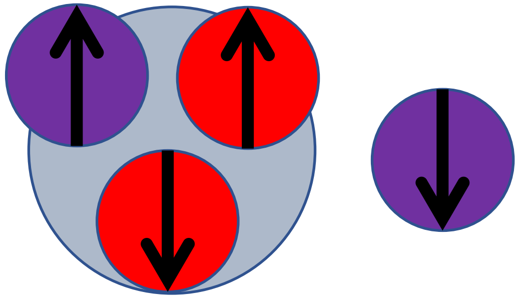
$$T_0 = Ne^{-nl\sigma_0 \frac{\lambda}{\lambda_0}}$$



Transmission!

Transmission of Polarized Neutrons through Polarized ^{3}He

$$T \ = Ne^{-nl\sigma_0 \frac{\lambda}{\lambda_0}}\left(\cosh\left(nl\sigma_0 \frac{\lambda}{\lambda_0} P_{He}\right) + P_n \sinh\left(nl\sigma_0 \frac{\lambda}{\lambda_0} P_{He}\right)\right)$$



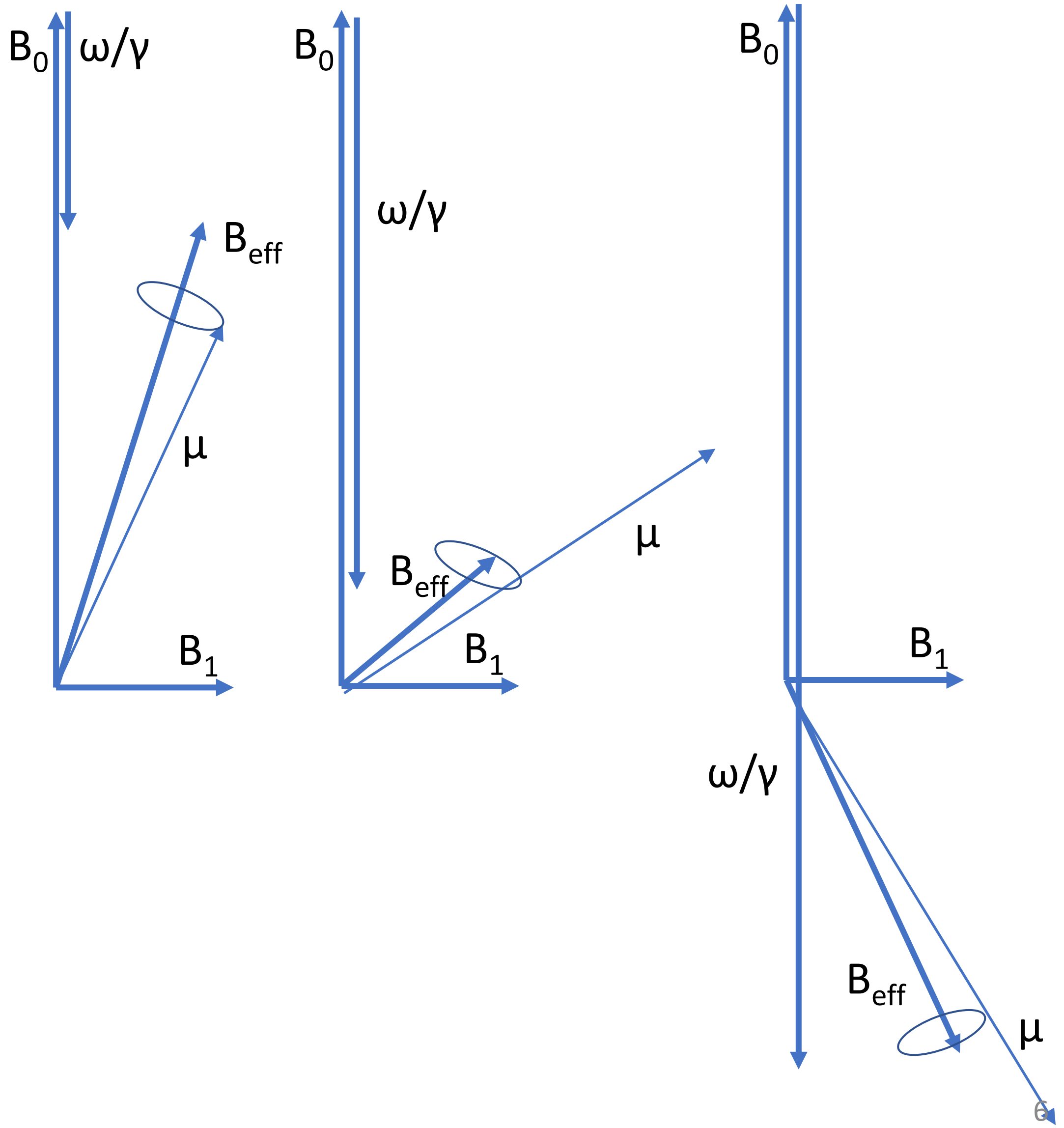
Absorption!

Polarimetry for the Nab Experiment

Adiabatic Fast Passage (AFP) Spin Flipping

Flipping the spin using a resonant field

- B_0 is a static field in the lab frame, B_1 oscillates with some frequency, ω.
- In the rotating frame, the magnetic moment sees an effective B_{eff}, and B_0, modulated by the larmor frequency and ω.
- Change in B_{eff} must be slower than the Larmor Precession Frequency



Polarimetry for the Nab Experiment

Measuring A Polarization

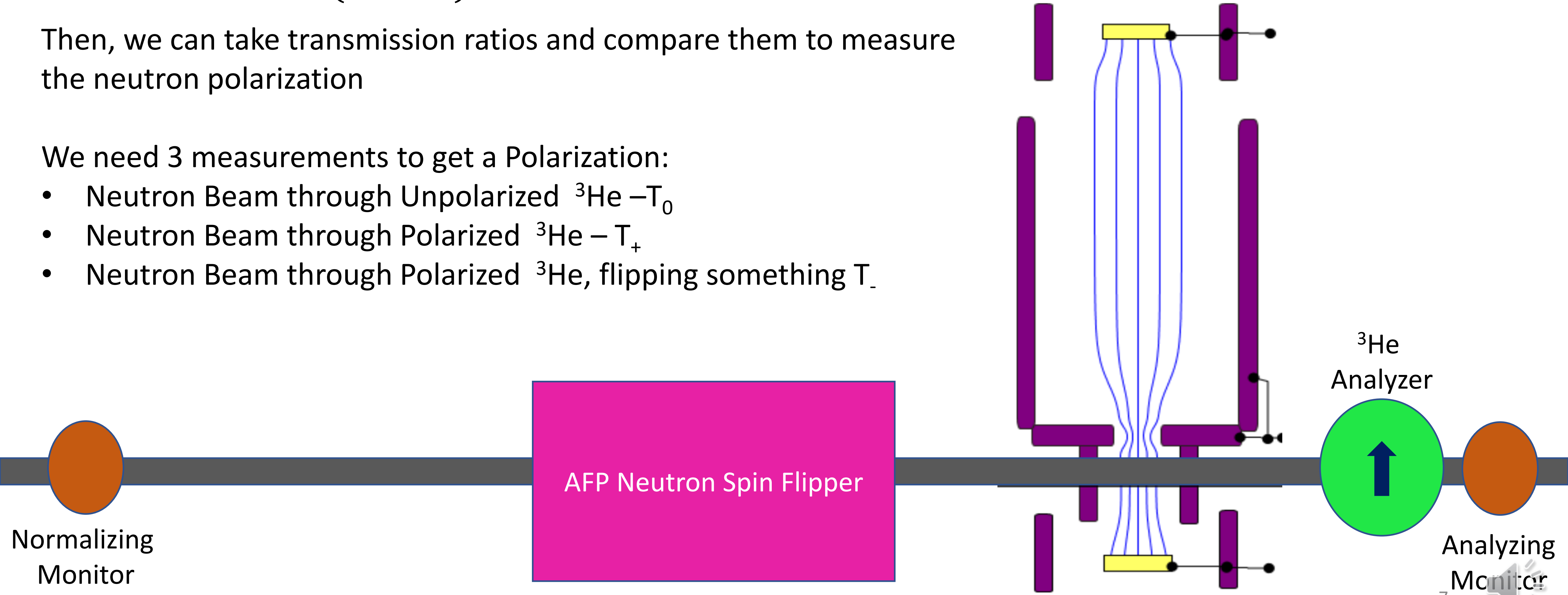
If we flip a spin, that spin gets multiplied a factor that depends of the efficiency of the flipping device

$$P \rightarrow (1 - 2\varepsilon)P$$

Then, we can take transmission ratios and compare them to measure the neutron polarization

We need 3 measurements to get a Polarization:

- Neutron Beam through Unpolarized ^{3}He –T_0
- Neutron Beam through Polarized ^{3}He – T_+
- Neutron Beam through Polarized ^{3}He, flipping something T_-



Normalizing Monitor

AFP Neutron Spin Flipper

^{3}He Analyzer

Analyzing Monitor

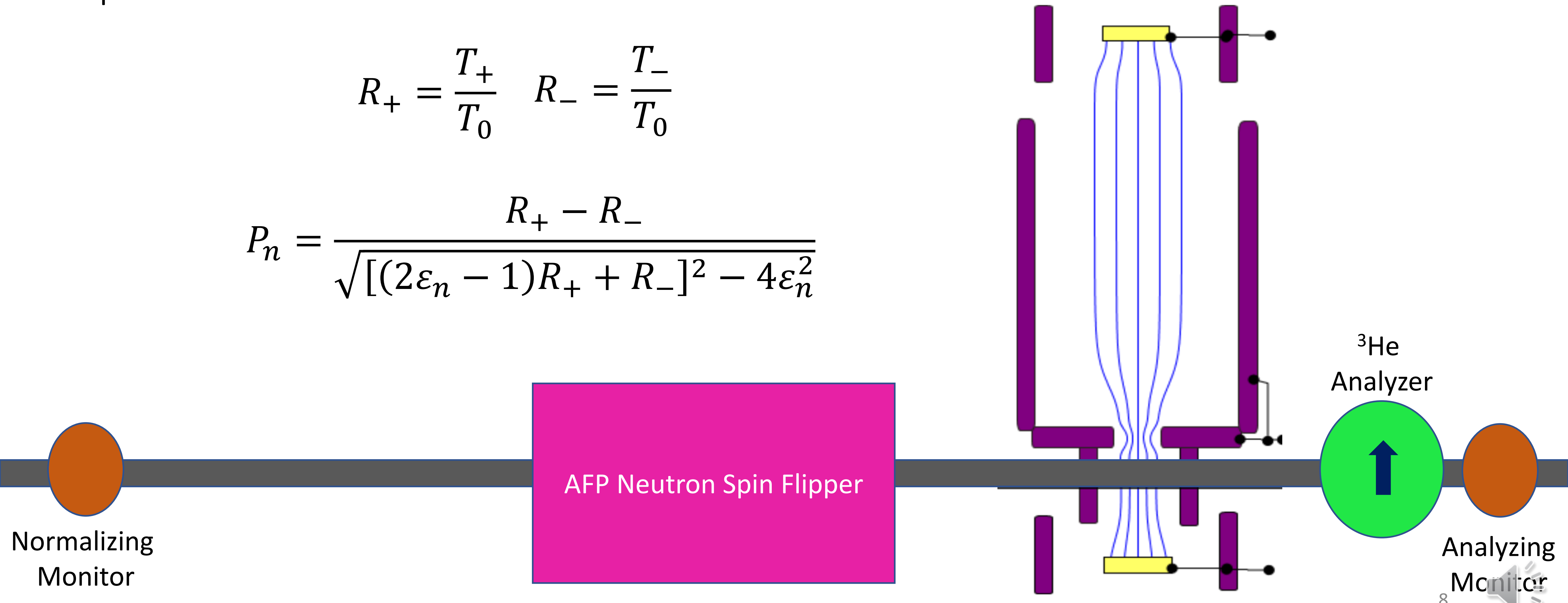
Polarimetry for the Nab Experiment

Measuring A Polarization by Flipping Neutrons

If we assume that our ^{3}He polarization is the same between measurements, we can compare ratios of transmission measurements

$$R_+ = \frac{T_+}{T_0} \quad R_- = \frac{T_-}{T_0}$$

$$P_n = \frac{R_+ - R_-}{\sqrt{[(2\varepsilon_n - 1)R_+ + R_-]^2 - 4\varepsilon_n^2}}$$



Normalizing Monitor

AFP Neutron Spin Flipper

^{3}He Analyzer

Analyzing Monitor

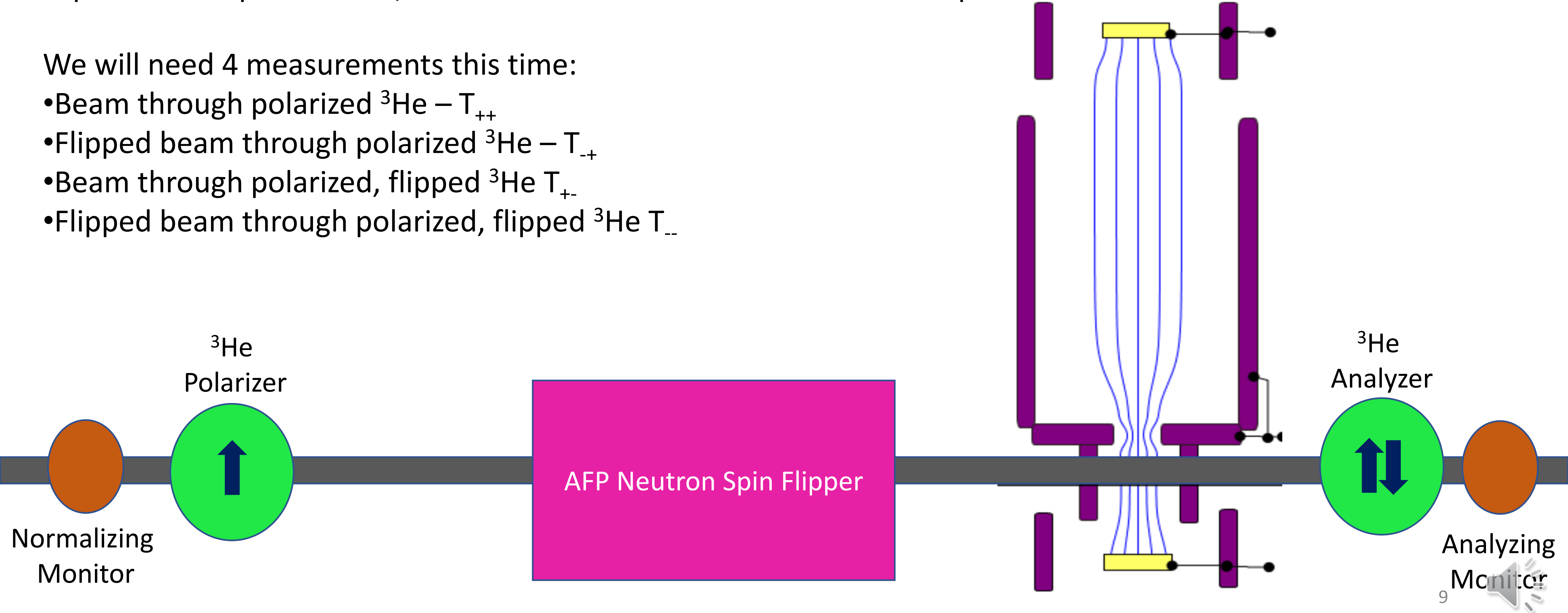
Polarimetry for the Nab Experiment

Measuring our Spin Flipper Efficiency

We need to understand our Spin Flipper Efficiency. We can’t do that on a beam where we expect a small polarization, so we will add a 3He Polarizer to our setup

We will need 4 measurements this time:

- Beam through polarized ^{3}He – T_{++}
- Flipped beam through polarized ^{3}He – T_{-+}
- Beam through polarized, flipped ^{3}He T_{+-}
- Flipped beam through polarized, flipped ^{3}He T_{--}



^{3}He Polarizer

AFP Neutron Spin Flipper

^{3}He Analyzer

Normalizing Monitor

Analyzing Monitor

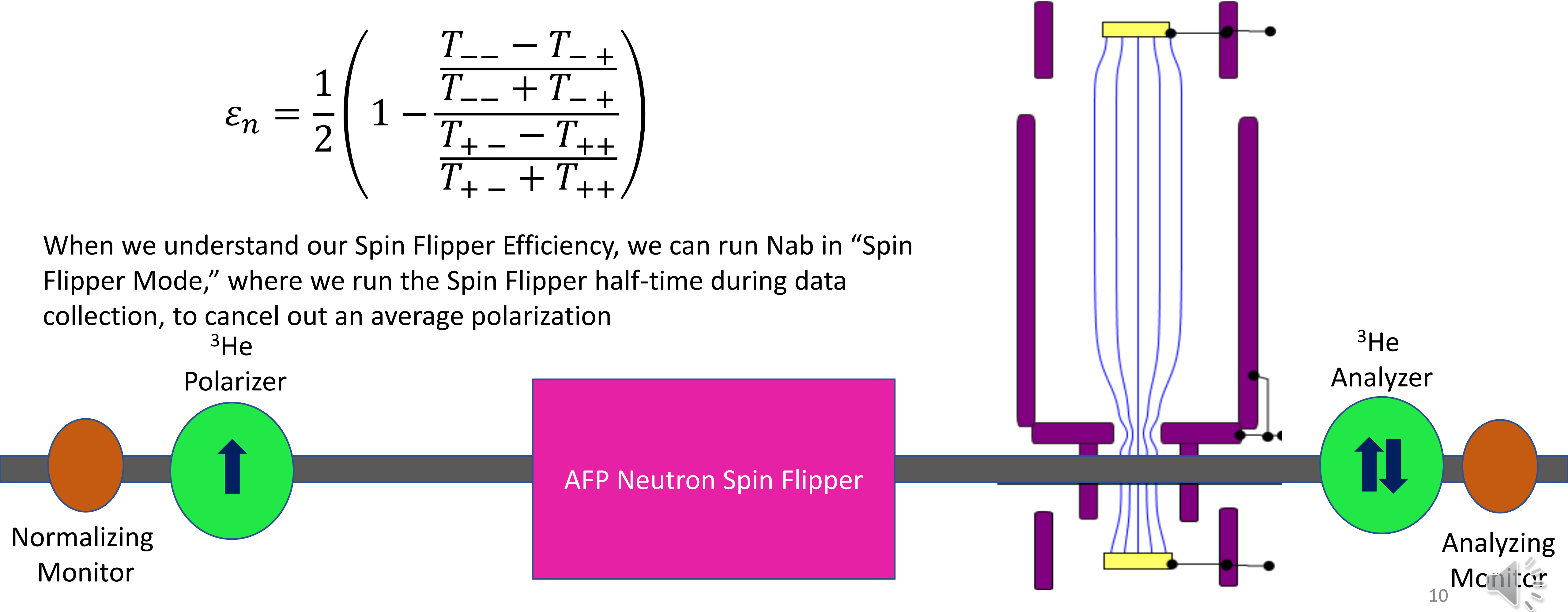
Polarimetry for the Nab Experiment

Measuring our Spin Flipper Efficiency

If we assume that the polarization of the polarizer and the analyzer are the same between measurements, we can take transmission ratios

$$\varepsilon_n = \frac{1}{2}\left(1 - \frac{\frac{T_{--} - T_{-+}}{T_{--} + T_{-+}}}{\frac{T_{+-} - T_{++}}{T_{+-} + T_{++}}}\right)$$

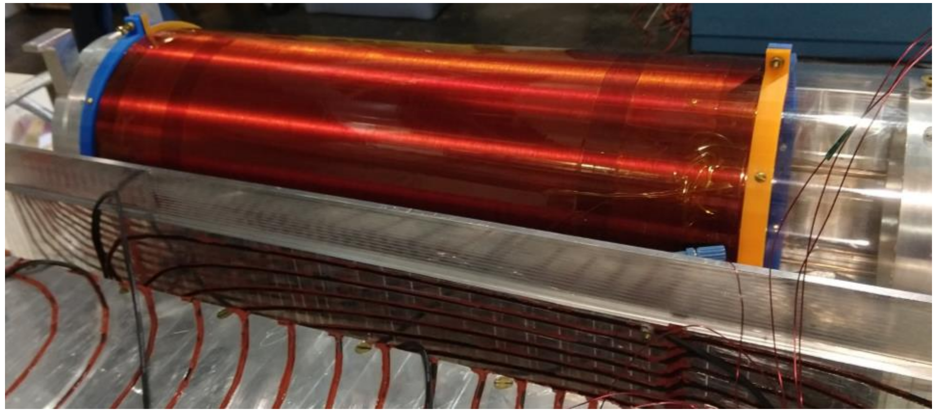
When we understand our Spin Flipper Efficiency, we can run Nab in “Spin Flipper Mode,” where we run the Spin Flipper half-time during data collection, to cancel out an average polarization

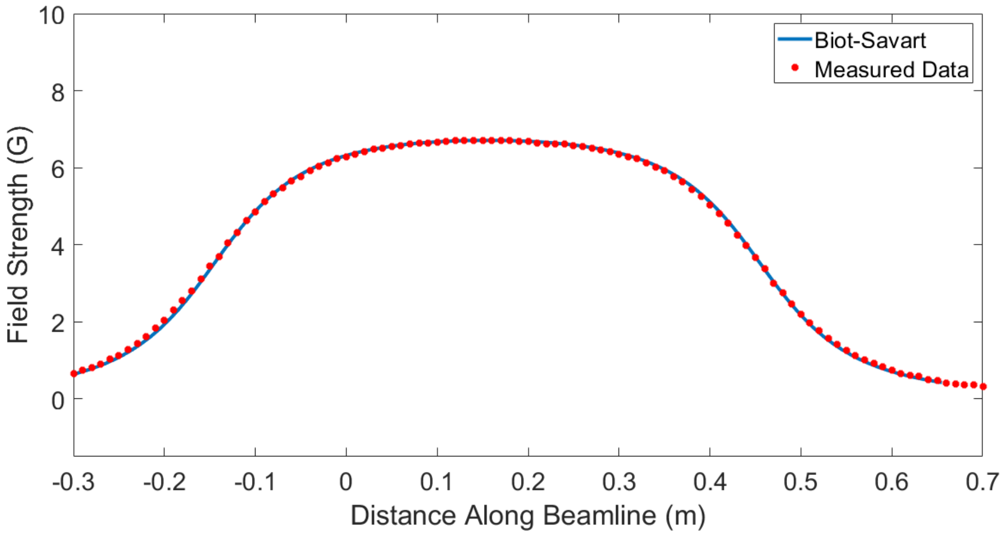


Equipment for Polarimetry

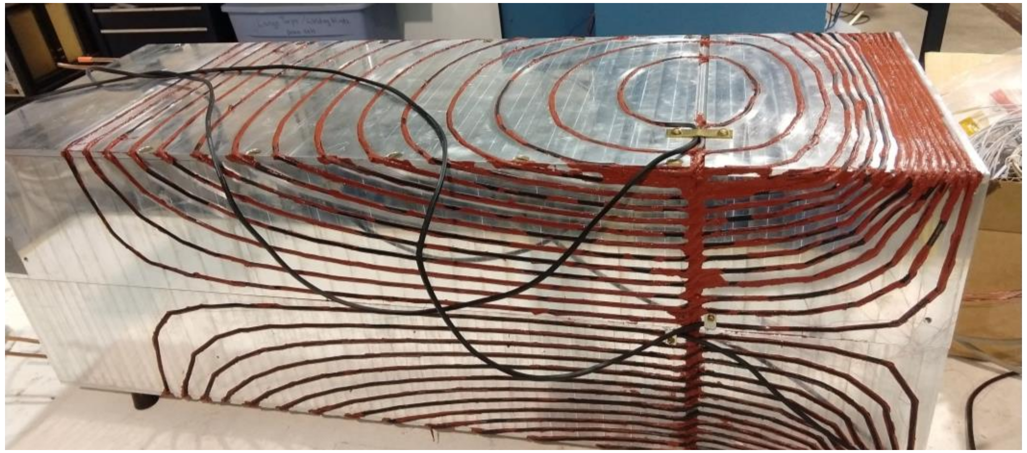
An Adiabatic Fast Passage Spin Flipper

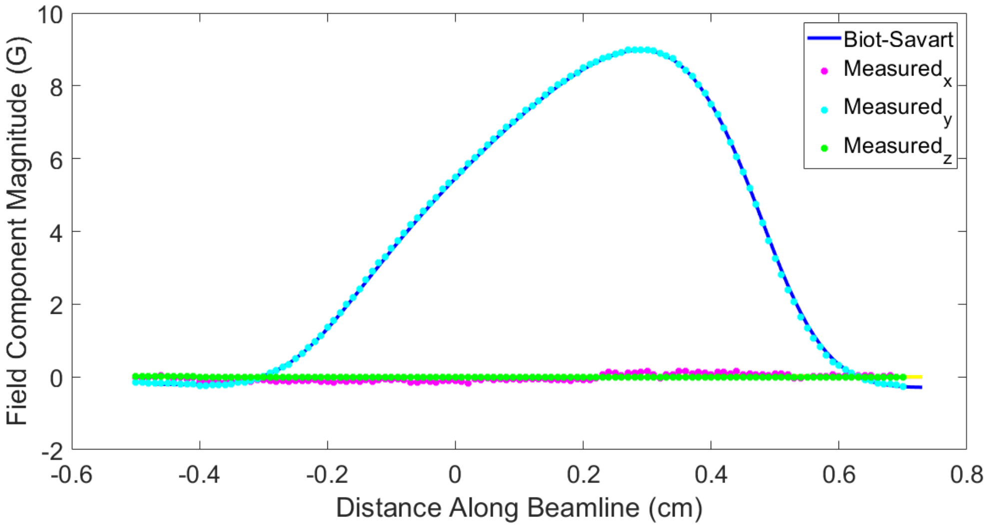
RF Solenoid





Static Gradient Field



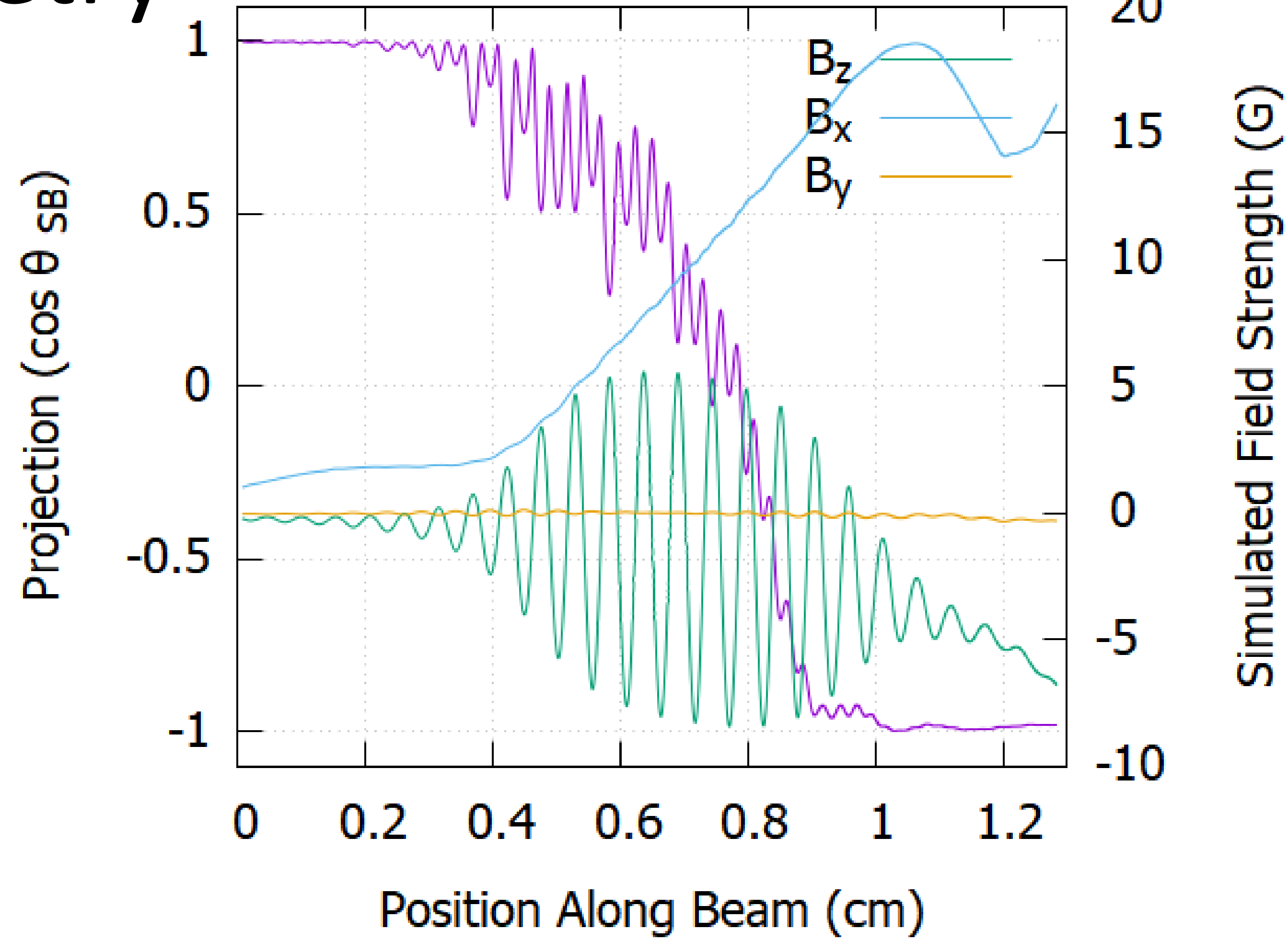


Equipment for Polarimetry

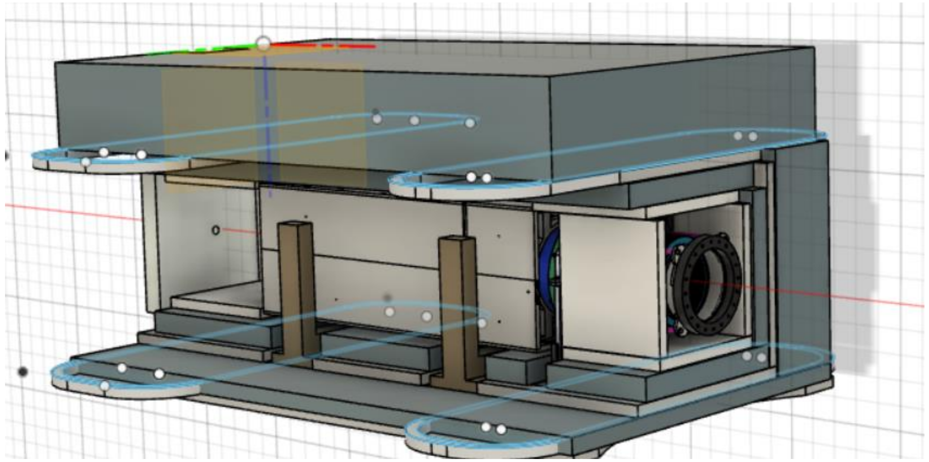
An Adiabatic Fast Passage Spin Flipper

We can integrate Bloch’s Equations, sampling the field at different points in time as the neutron travels through it.

Simulations like this help us predict how well our Spin Flipper will function in different fields, so that we can also include the effects of the spectrometer field, and learn how to compensate for those with auxiliary coils:



The cosine of the angle plotted here is the angle between the spin and the field in the lab frame (purple)



Equipment for Polarimetry

^{3}He Holding Fields

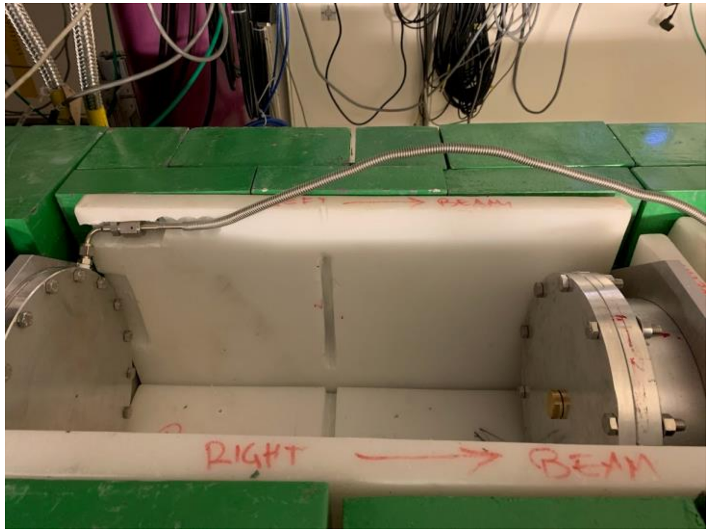
We need our ^{3}He Polarization to be consistent across our measurement, but it will decay as the ^{3}He atoms move about in the cell and experience different field gradients.
We want to minimize our field gradients to prolong ^{3}He polarization lifetime.

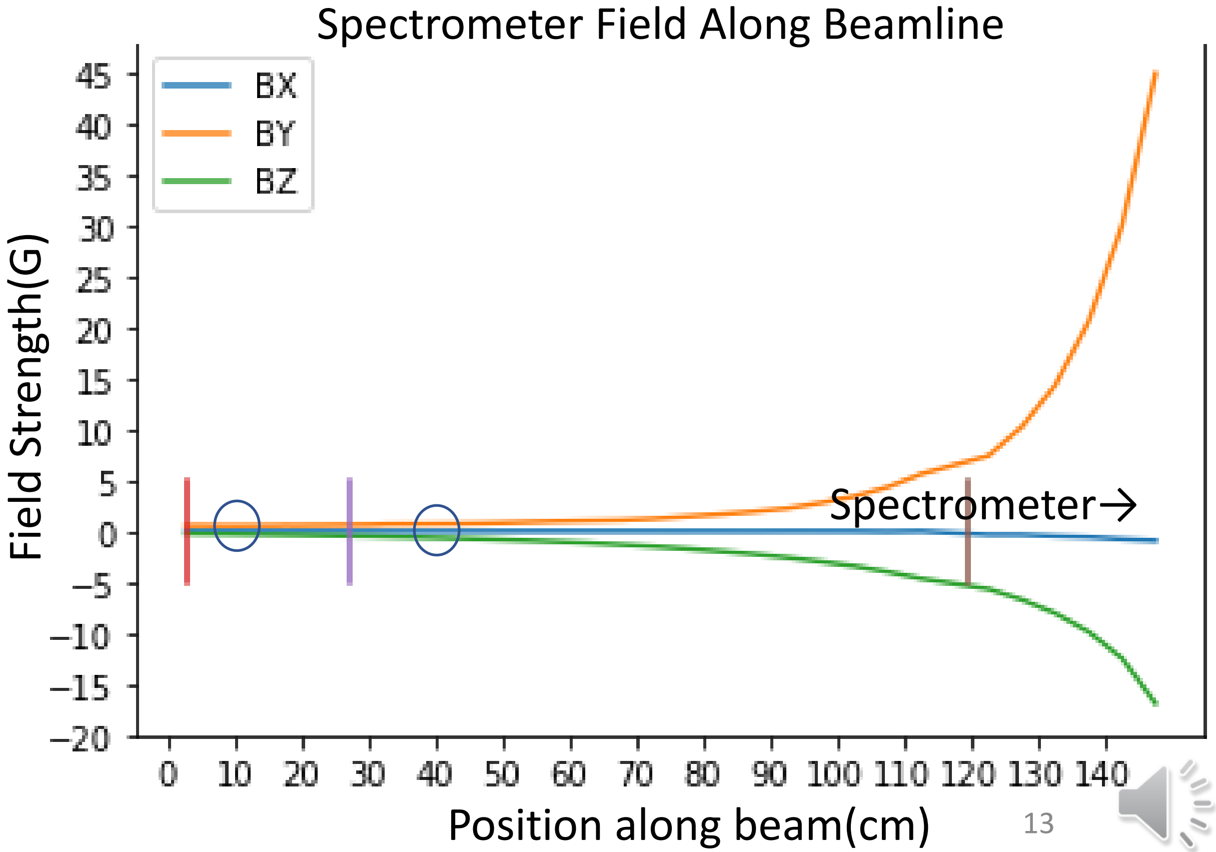
Problem:

The fields from our spectrometer produce gradients in these regions

$$\frac{1}{T_1} \propto \frac{|\nabla B_x|^2 + |\nabla B_y|^2}{B^2}$$

We have very limited space inside the shielding to produce the holding fields we need and control these gradients

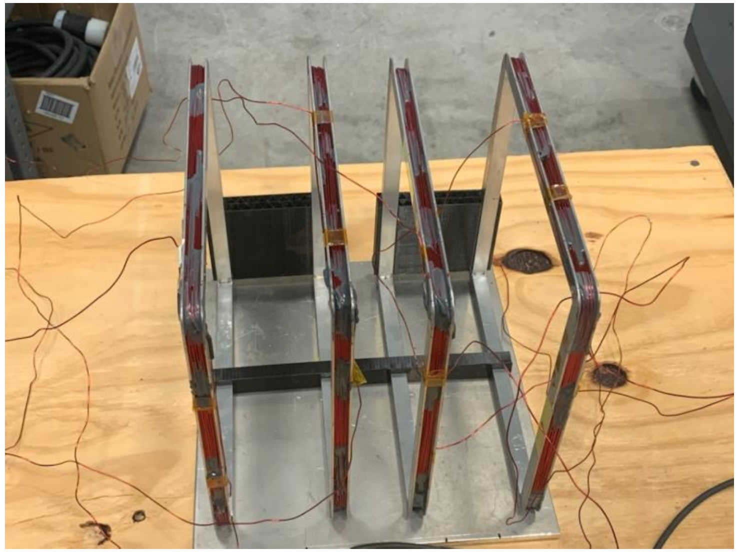


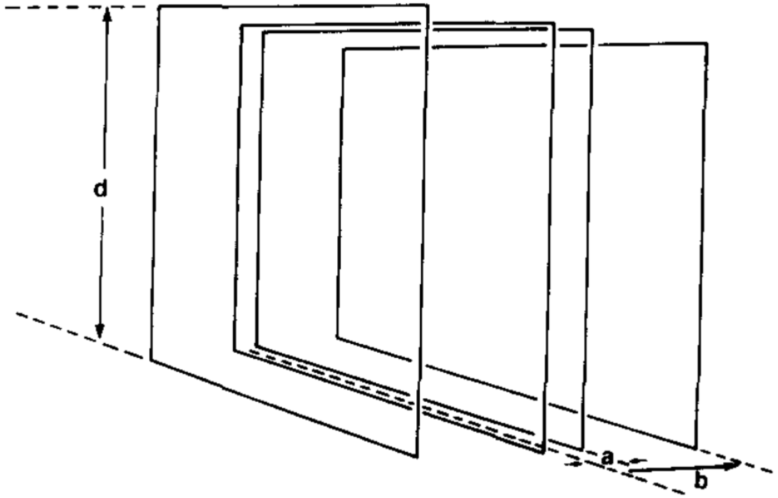


Equipment for Polarimetry

^{3}He Holding Fields

Solution: Merritt Coils





Review of Scientific Instruments 54, 879 (1983); https://doi.org/10.1063/1.1137480

What We Designed:

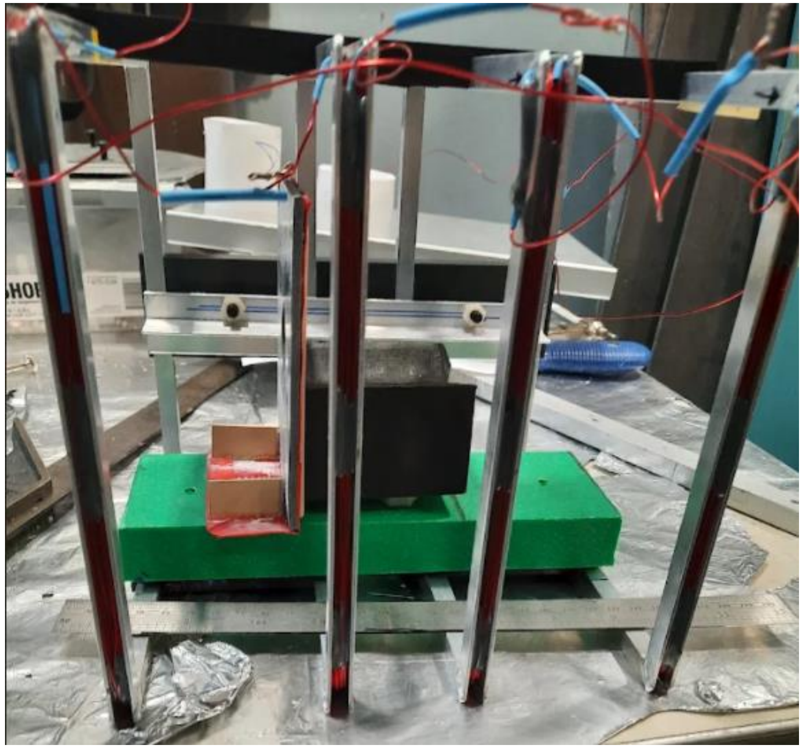
- 2 sets of Merritt Coils

	Upstream Coil	Downstream Coil
Size (d)	200mm	220mm
a (distance between center and inner pair)	25.6mm	28.2mm
b (distance between center and outer pair)	101.1mm	111.2mm
Inner Pair Turns	11	36
Outer Pair turns	26	85
Current for 10G at center	4.285A	1.44A
Simulated Relative Gradient over 10cm cube at center	5.09×10^{-6}	2.93×10^{-6}

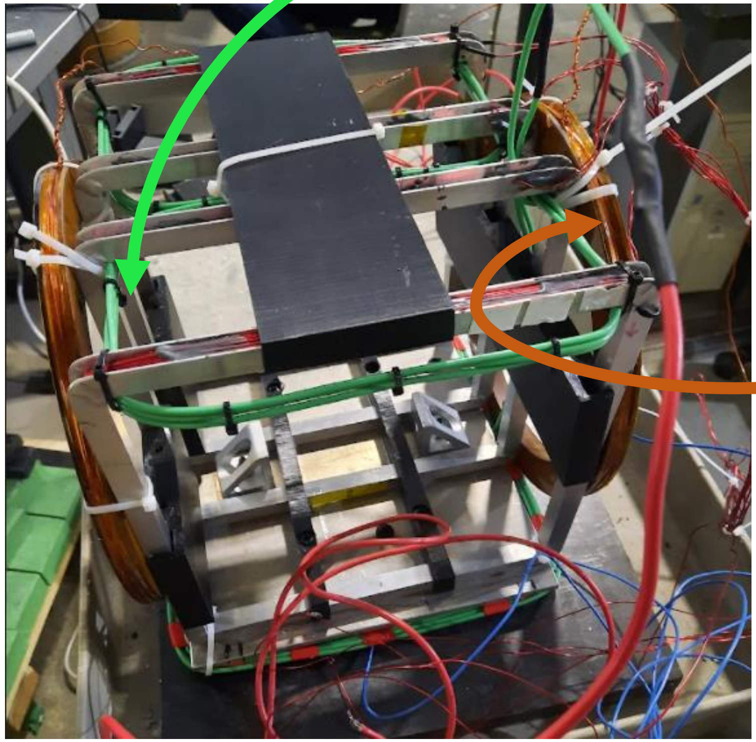
Equipment for Polarimetry

^{3}He Holding Fields

Solution: Merritt Coils



Upstream Merritt Coil
^{3}He Cell Scotty
Measured lifetime on Beamline: 44.3 +- 7.7 hrs
This cell is smaller and further away from the spectrometer. we get an OK lifetime

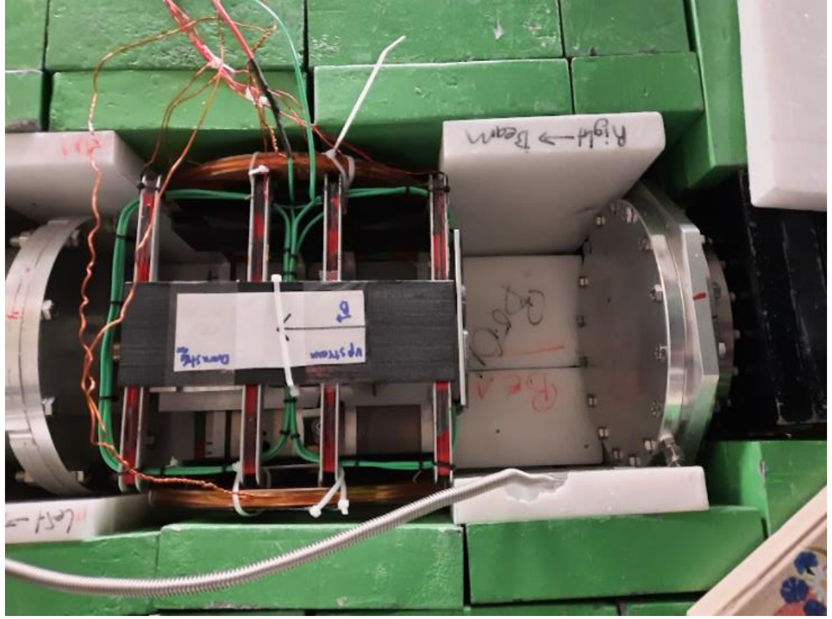


Compensation for Spectrometer (green)

AFP Sweep Coils (brown)

Downstream Merritt Coil
^{3}He Cell Hedy Lamar
Measured lifetime on Beamline:In Progress (Requires further tuning)
Lifetime in Lab: 49+- 10.4 h
This cell is larger and closer to spectrometer the spectrometer, which makes the lifetime shorter.

Polarimetry



Estimate ^{3}He lifetime ~30hrs in full fields:

% of Helium polarization lost during:

- 1 neutron pulse (1/60s): 1.157e-05
- 60 neutron pulses (1s): 0.0006944
- 600 neutron pulses (10s): 0.006944
- 3600 neutron pulses (60s): 0.0416

We will fit neutron data for the ^{3}He polarization in situ. We can attempt to match or group data with similar ^{3}He polarizations.

- FID data is often noisy, and only yields a relative polarization measurement

We should be able to compare measurements that are over a minute apart, and still not be able to resolve the change in polarization. This also sets the time over which we want to think about flipping our systems, and canceling drifts:

- We will monitor temperatures of various devices, and currents to watch for drifts that may affect the efficiency of the Spin Flipper.
- We will also monitor the incoming neutron beam with an upstream monitor to normalize and correct for fluctuations in beam power.

Polarimetry : June 2022

What's Next? Neutrons!

- DS Merritt Coil needs further tuning.
- Mu-Metal shielding for Merritt Coils to reduce effects of outside fields
- New neutron monitor needs calibrated
- Need to measure thickness of ^{3}He cells
    - Fit neutron spectra through unpolarized cells

- Take Data!

The Nab Collaboration

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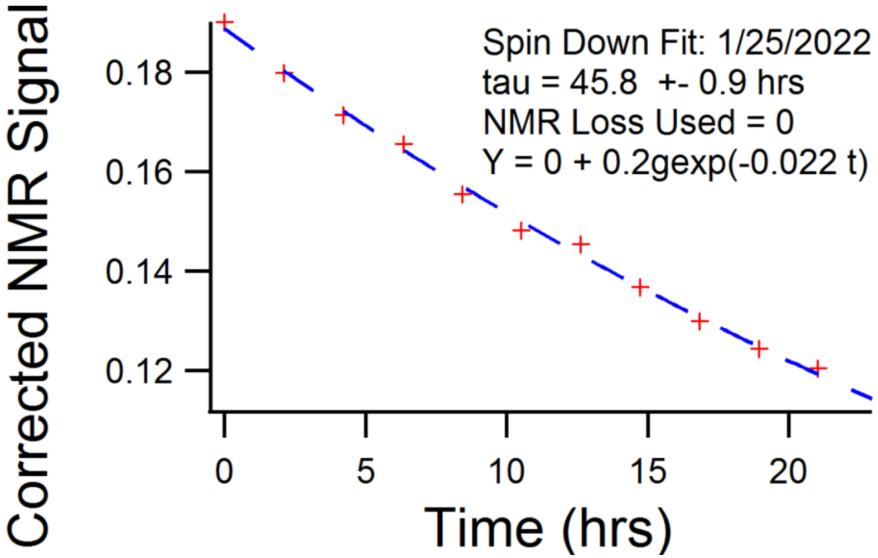
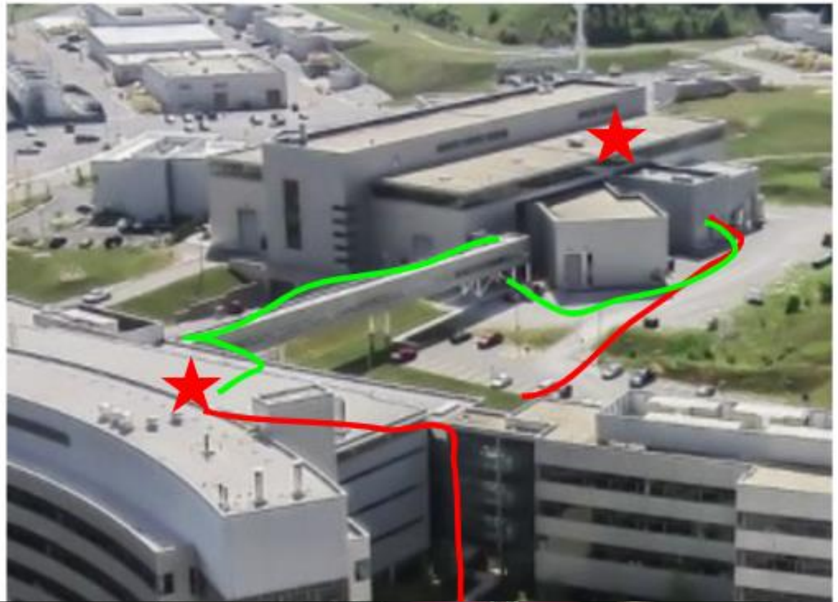
Main Project Funding:

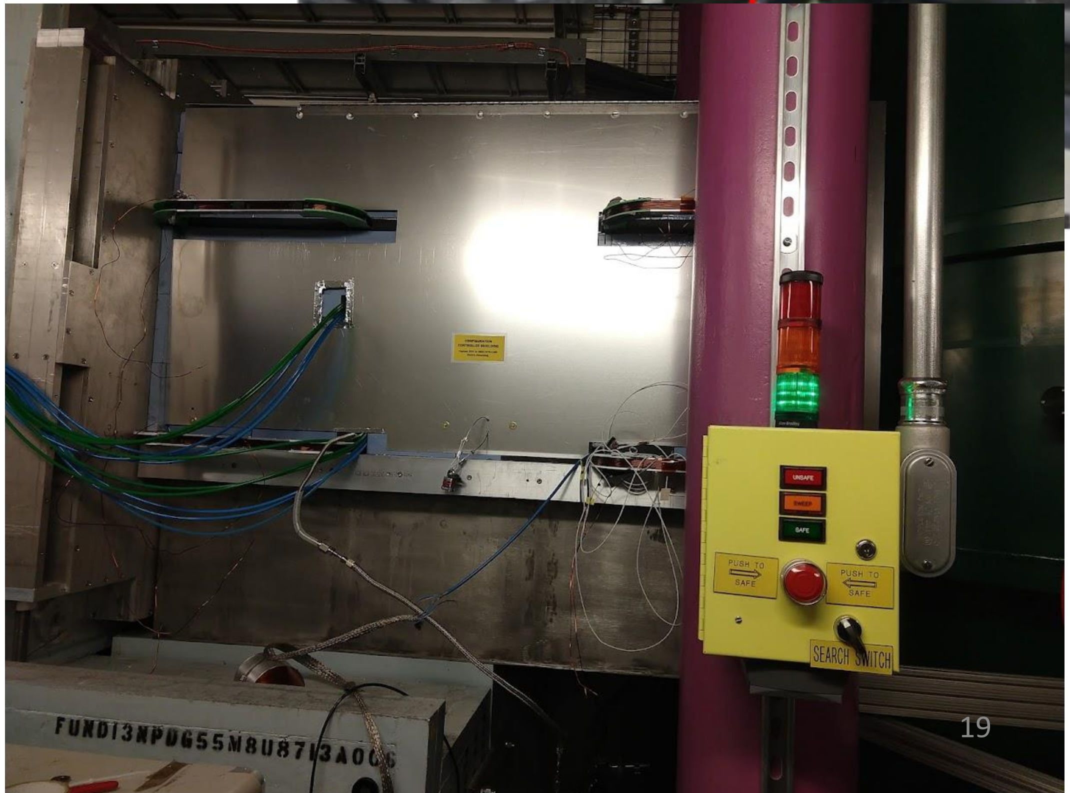
Equipment for Polarimetry

Measuring ^{3}He Polarization Lifetime

- Polarize ^{3}He cell using Spin Exchange Optical Pumping
- Transfer Cell to environment
  - We lose some polarization in this process
- Measure relative polarization using Free Induction Decay (FID) over various timing intervals (hrs)
- Use the amplitude of the FID signals to examine the decay of polarization over time







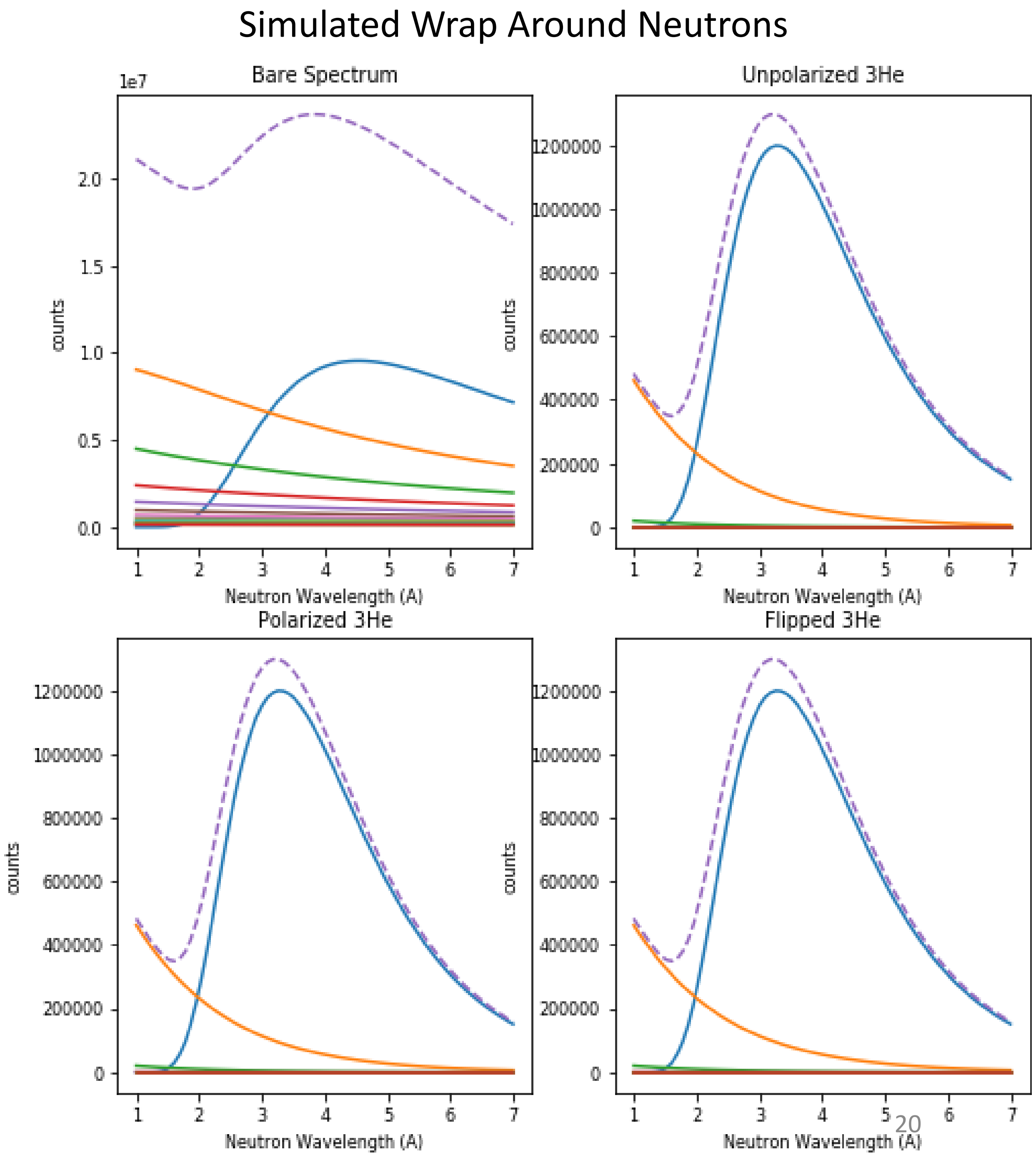
Polarimetry

Our DAQ takes “frames” of data at a rate of 60Hz

- This coincides with the neutron pulses from the SNS
- Neutron pulses overlap
  - We have concerns about the Choppers imparting or modifying the polarization of the beam, so we will need to be able to examine the overlapping specra from the monitor.
  - We can fit for spectrum parameters and reconstruct a single pulse

We will monitor temperatures of various devices, and currents to watch for drifts that may affect the efficiency of the Spin Flipper.

We will also monitor the incoming neutron beam with an upstream monitor to normalize and correct for fluctuations in beam power.


Simulated Wrap Around Neutrons

Polarimetry for the Nab Experiment

Measuring A Polarization by Flipping ^{3}He

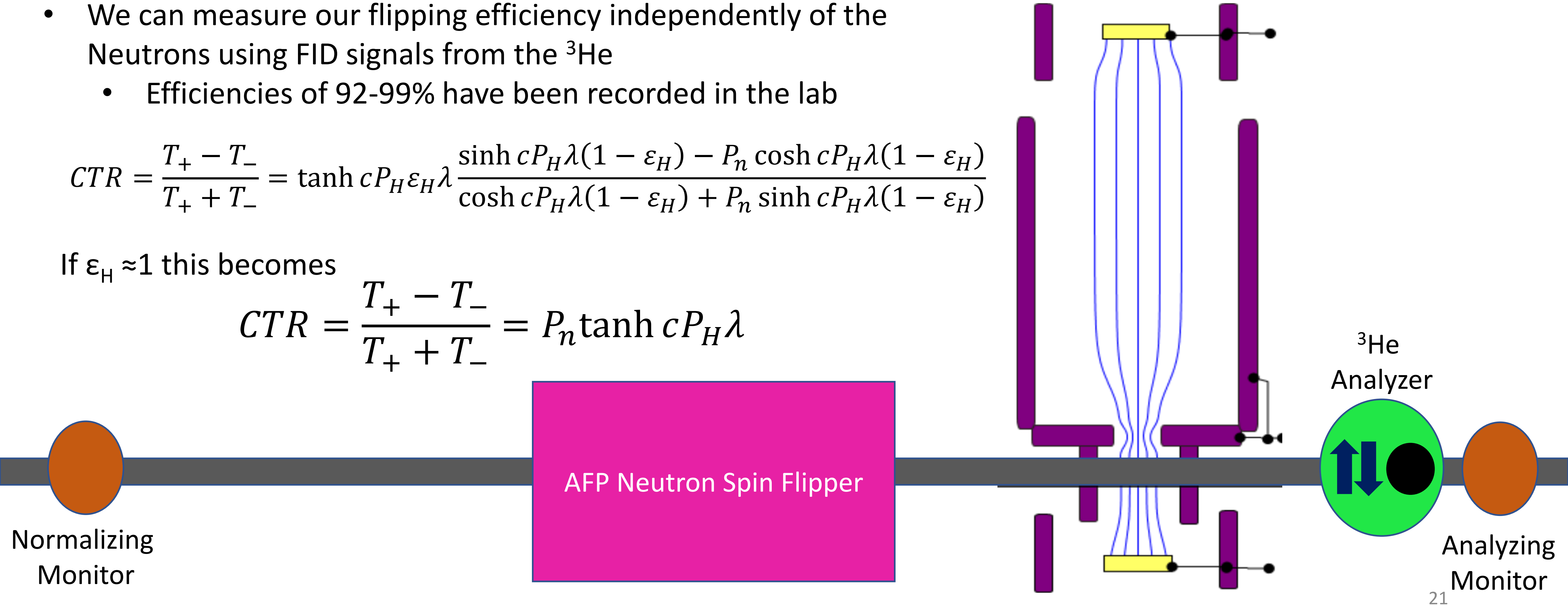
Flipping the ^{3}He yields a more complicated analysis, but might be more easily achievable

- We can measure our flipping efficiency independently of the Neutrons using FID signals from the ^{3}He
  - Efficiencies of 92-99% have been recorded in the lab

$$CTR = \frac{T_+ - T_-}{T_+ + T_-} = \tanh cP_H\varepsilon_H\lambda \frac{\sinh cP_H\lambda(1-\varepsilon_H) - P_n \cosh cP_H\lambda(1-\varepsilon_H)}{\cosh cP_H\lambda(1-\varepsilon_H) + P_n \sinh cP_H\lambda(1-\varepsilon_H)}$$

If $\varepsilon_H \approx 1$ this becomes

$$CTR = \frac{T_+ - T_-}{T_+ + T_-} = P_n \tanh cP_H\lambda$$



The Nab Experiment

Systematic Uncertainties

Experimental parameter	**Main specification**	$(\boldsymbol{\Delta a/a})_{syst}$
Magnetic field		
... curvature at pinch	$\Delta\gamma/\gamma = 2\%$ with $\gamma = d^2\, B_z(z)/dz^2/B_z(0)$	**$5.3\cdot10^{-4}$**
… ratio $r_B = B_{TOF}/B_0$	$(\Delta r_B)/r_B = 1\%$	$2.2\cdot10^{-4}$
… ratio $r_{B,DV} = B_{DV}/B_0$	$(\Delta r_{B,DV})/r_{B,DV} = 1\%$	$1.8\cdot10^{-4}$
Length of the TOF region		none
Electric potential inhomogeneity:		
… in decay volume / filter region	$\lvert U_F - U_{DV}\rvert < 10$ mV	**$5\cdot10^{-4}$**
… in TOF region	$\lvert U_F - U_{TOF}\rvert < 200$ mV	$2.2\cdot10^{-4}$
Neutron beam:		
… position	$\Delta\overline{z_{DV}} < 2$ mm	$1.7\cdot10^{-4}$
… profile (including edge effect)	Slope at edges < 10%/cm	$2.5\cdot10^{-4}$
… Doppler effect		small
… Unwanted beam polarization	**$P_n<2\cdot10^{-5}$**	$1\cdot10^{-4}$
Adiabaticity of proton motion		$1\cdot10^{-4}$
Detector effects:		
… Electron energy calibration	$\Delta E < 0.2$ keV	$2\cdot10^{-4}$
… Shape of electron energy response	fraction of events in tail to 1%	**$4.4\cdot10^{-4}$**
… Proton trigger efficiency	$\epsilon_p < 100$ ppm/keV	$3.4\cdot10^{-4}$
… TOF shift due to detector/electronics	$\Delta t_p < 0.3$ ns	$3.9\cdot10^{-4}$
Electron TOF		small
Residual gas	$p < 2\cdot10^{-9}$ torr	$3.8\cdot10^{-4}$ (prelim.)
TOF in acceleration region	$\Delta r_{ground\ el.} < 0.5$ mm	$3\cdot10^{-4}$ (prelim.)
Background / Accidental coincidences		small
Sum		**$1.2\cdot10^{-3}$**